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Dynamic plane strain thermomechanical deformations of a thermally softening viscoplastic body subjected to compressive loads on the top and bottom faces are studied with the objective of exploring the initiation and development of a shear band from the site of the defect. It is found that, irrespective of the way the material inhomogeneity is modeled, a shear band initiates from the site of the defect and propagates in the direction of maximum shearing.

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Watertown, Massachusetts 02172-0001

Shear Band Development in Dynamic Plane
Strain Compression of a Viscoplastic Material

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Adiabatic shear banding is the name given to a localization phenomenon that occurs during high-rate plastic deformation. Practical interest in the phenomenon derives from the fact that once a shear band has formed, subsequent deformations of the body occur in this narrow region with the rest of the body undergoing very little *deformations*. Thus shear bands are often precursors to shear fractures.

Earlier work [1-3] on the adiabatic shear banding problem involved analyzing the simple shearing *deformations* of a viscoplastic body. Recently Needleman [4] and Batra and Liu [5] have studied the initiation and growth of shear bands in plane strain deformations of a softening material. Needleman [4] analyzed a purely mechanical problem, approximated the effect of thermal softening by assuming the existence of a peak in the stress-strain curve and modeled a material inhomogeneity/flaw by presuming that the flow stress for a small amount of material near the center of the block was less than that of the surrounding material. Batra and Liu [5] studied the coupled thermomechanical deformations of a thermally softening viscoplastic solid and modeled the material inhomogeneity by introducing a temperature bump at the center of the block whose boundaries were taken to be perfectly insulated. Two different loadings namely those corresponding to simple shearing and simple compression of the block were considered. Here we examine the effect of (a) modeling the material inhomogeneity in two different ways, namely introducing a temperature perturbation and assuming the existence of a weak material, (b) introducing two defects place symmetrically on the vertical axis of the block, (c) varying the reduction in the flow stress of the weak material, and (d) two different sets of initial conditions.

Fig. 1a is a sketch of the undeformed and homogeneously deformed shape of the block. In terms of non-dimensional variables, the governing equations are:

$$\dot{\rho} + \rho\, v_{i,i} = 0 \ ,$$

$$\delta\widetilde{\rho}\, \dot{v}_i = T_{i\alpha,\alpha} \ ,$$

$$\widetilde{\rho}\dot{\theta} = \beta\, \theta_{,\alpha\alpha} + (\widetilde{\rho}/\rho_r)\, [1/(\sqrt{3}\, I)]\, (1+bI)^m (1-\nu\theta) D_{ij}\, D_{ij} \ ,$$

$$\sigma_{ij} = -B(\rho - 1)\, \delta_{ij} + [1/(\sqrt{3}I)]\, (1+bI)^m (1-\nu\theta) D_{ij} ,$$

$$T_{i\alpha} = \widetilde{\rho}/\rho\, X_{\alpha,j}\, \sigma_{ij}, \quad 2D_{ij} = v_{i,j} + v_{j,i},$$

$$2I^2 = \widetilde{D}_{ij}\, \widetilde{D}_{ij}, \quad \widetilde{D}_{ij} = D_{ij} - \frac{1}{3}\, D_{kk}\, \delta_{ij}$$

Here ρ is the present mass density, v_i the velocity of a material particle, $\tilde{\rho} = \rho_o/\rho_r$, $\delta = \rho_r v_o^2/\sigma_o$, ρ_r is the mass density in the stress-free reference configuration, ρ_o is the mass density in the reference configuration, σ_o is the yield stress in a quasistatic simple tension or compression test, σ_{ij} is the Cauchy stress tensor, θ is the temperature change, and β, m and ν are material parameters. These equations are written in terms of rectangular cartesian coordinates, a comma followed by i or α implies partial differentiation with respect to x_i or X_α, and a repeated index implies summation over the range of the index.

We study only those deformations that remain symmetric about the horizontal and vertical planes passing through the center of the block. Thus, we analyze the deformations of the material in the first quadrant. The use of the Galerkin method and the lumped mass matrix reduces the governing equations to a set of coupled nonlinear ordinary differential equations which are integrated by using the IMSL subroutine LSODE. We use the 9-noded quadrilateral element and do not a priori align the sides of the elements so that they are along the direction of the maximum shearing at the instant of the initiation of a shear band.

Figure 1b depicts the stress-strain curve for plane strain uniform compression of the block deformed at a nominal strain rate of 5,000 per sec. Because of the rather high value assumed for the coefficient ν of thermal softening the material softening caused by the heating of the material exceeds the hardening due to strain-rate effects right from the beginning.
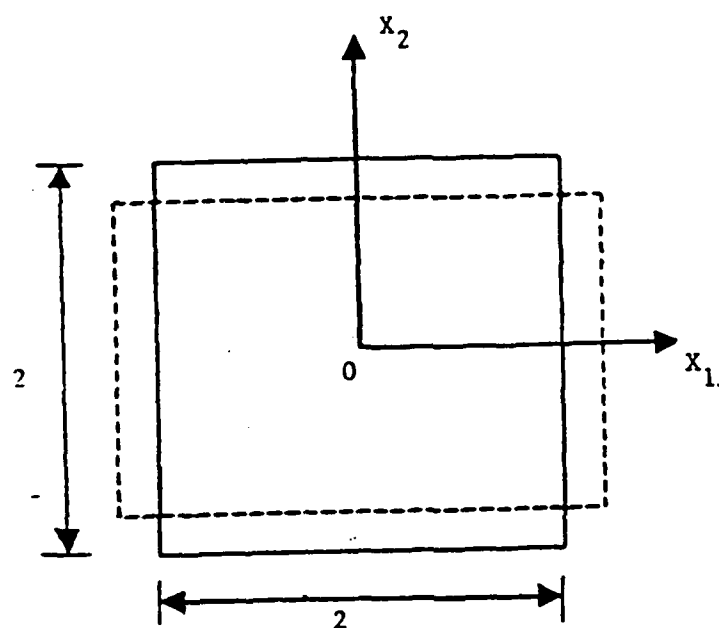
Fig. 2 shows the contours of the second invariant I of the deviatoric strain-rate tensor at successively higher values of the average strain γ_{avg} when the material defect is modeled by introducing a temperature perturbation centered around the point P (0.0, 0.375). In each case, the peak value I_{max} of I occurs at the point P where the temperature is maximum. At an average strain of 0.04, $I_{max} = 11.44$ implying thereby that the material surrounding it is deforming at a strain-rate greater than 50,000 sec^{-1}. For $\gamma_{avg} = 0.04$, $\theta_{max} = 0.341$ occurs at P and equals 68.2 percent of the presumed melting temperature of the material. The contours of I originate at the point P and then fan out along the direction of maximum shearing. There appear to be sources of energy building up at the point P and three other points on the boundary where the parallelogram through P with adjacent sides making angles of $\pm45°$ with the horizontal axis intersect it. When there is sufficient energy built up at these points contours of successively higher values of I originate from these points and propagate along the direction of maximum shearing. Also as the deformation of the block progresses, these contours become narrower implying thereby that severe deformations are localizing into thin bands.

Similar results are obtained for the other cases. Thus, irrespective of the way a material inhomogeneity is modeled, a shear band initiates from the site of the defect and propagates in the direction of maximum shearing. The value of the average strain at the instant of the initiation of the band depends upon the strength of the material defect introduced. Once the shear band reaches the boundaries of the block it is reflected back, the angle of reflection being nearly equal to the angle of incidence.

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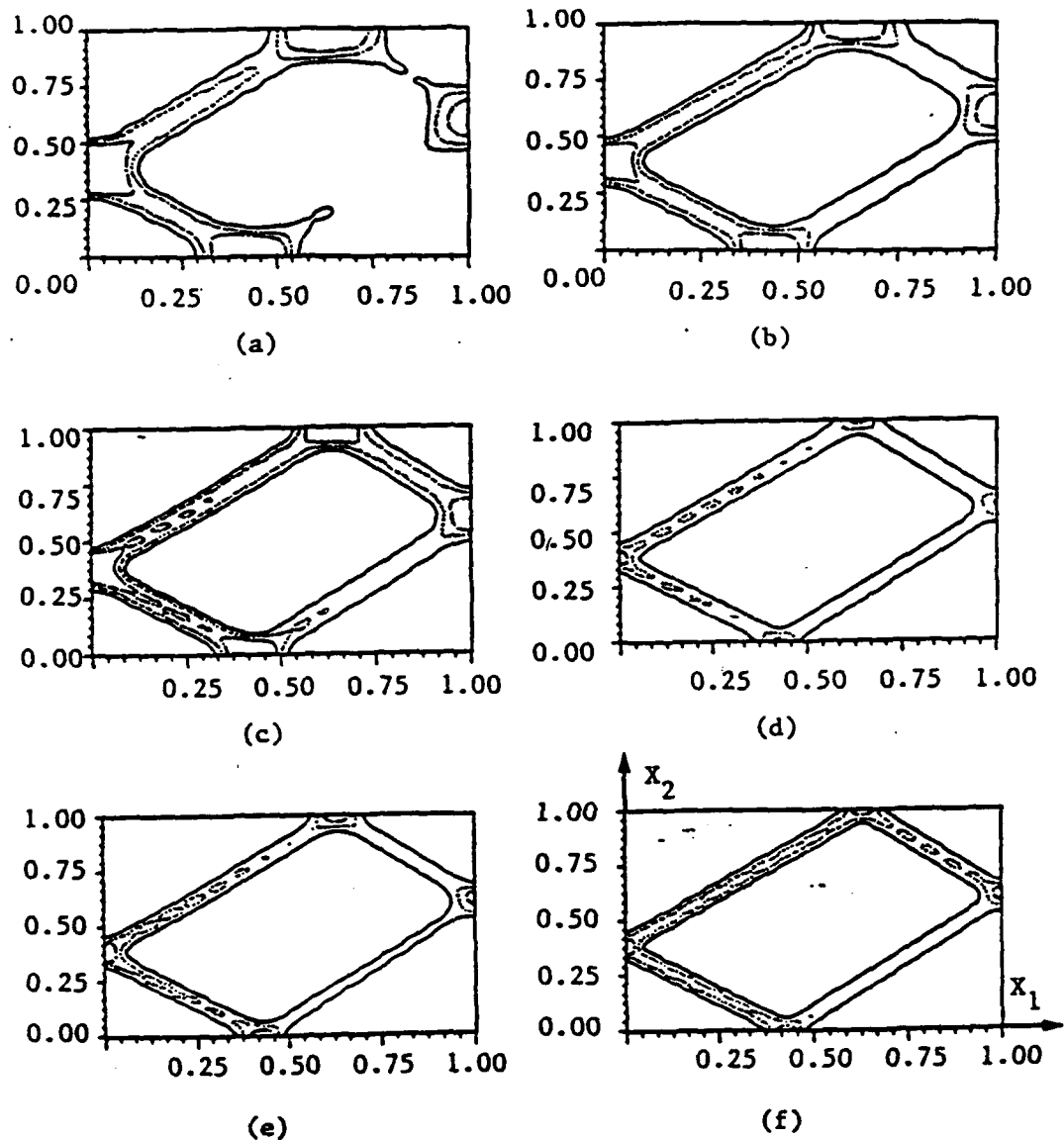
(a) The problem studied.

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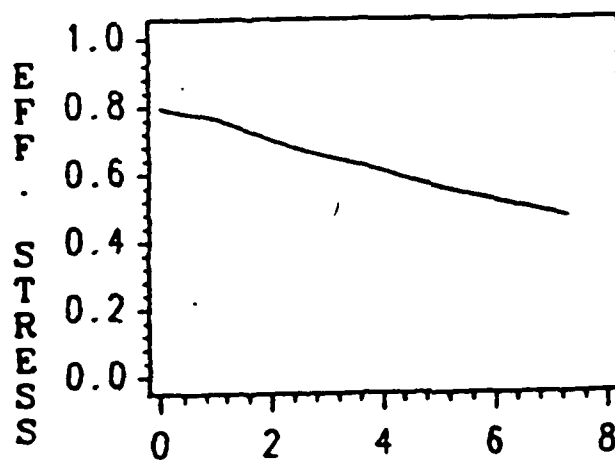
(b) Stress-strain curve in simple compression for the material studied.

Figure 1

Figure 2

Contours of the second invariant I of the deviatoric strain-rate tensor at different values of the average strain when the material defect is modeled by a temperature perturbation.

(a) $\gamma_{avg} = 0.02$, $I_{max} = 3.5$; _____ 1.50, ... 1.75, —·—·— 2.0.

(b) $\gamma_{avg} = 0.025$, $I_{max} = 4.51$; _____ 1.50, ... 2.0, —·—·— 2.5.

(c) $\gamma_{avg} = 0.030$, $I_{max} = 4.83$; _____ 1.50, ... 2.0, —·—·— 2.5.

(d) $\gamma_{avg} = 0.035$, $I_{max} = 7.91$; _____ 2.50, ... 3.75, —·—·— 5.0.

(e) $\gamma_{avg} = 0.0375$, $I_{max} = 10.51$; _____ 2.50, ... 5.0, —·—·— 7.5.

(f) $\gamma_{avg} = 0.040$, $I_{max} = 11.44$; _____ 2.50, ... 5.0, —·—·— 7.5.